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Wood innovation in the residential construction sector; opportunities and constraints

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Abstract

We study the opportunities to increase the use of wood in the Dutch residential construction sector and assess the effects on material related CO_2 emission. Four house types are modeled with increasing quantities of wood used in constructions. CO_2 emission reductions of almost 50% are technically possible. We assess the innovation characteristics of these wood applications to create insights in the complexity of the necessary change process. Then we relate the innovation characteristics of the wood options to the context in which implementation of the technologies take place. The options vary strongly in the required technical and network changes and so do the opportunities to implement them. Based on this we expect that a 12% CO_2 emission reduction related to material use for residential buildings is possible in the short term by an increased share of wood use. We also study the possibilities for increased wood recycling practices. A large technical potential exists. To achieve this potential a significant policy effort is needed since significant changes in both technical and network dimensions are necessary. To stimulate innovation in the use of wood in residential construction, important focus points of policy making should be the culture in the Dutch construction sector, the way new building projects are commissioned, research areas within the building sector, and stabilization of building networks. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Wood is an important building material; it is a lightweight material easy to process and repair, and it is widely available to the construction industry. In addition, wood is potentially a CO_2 neutral material if produced in a sustainable way; it takes up as much CO_2 during growth as it releases during decay or combustion. Since the production of wood also requires relatively little energy for forestry and wood processing, it can be defined as a 'low energy building material' (Frühwald, 1996). Several studies have focused on the energy and CO_2 effects of using wood in the construction sector to replace other materials like concrete and steel. They show that CO_2 emissions related to material use in the construction sector can be reduced by 30–85% (Buchanan and Honey, 1996; Suzuki et al., 1995; Koch, 1992). For an overview of a number of options to rearrange material use in the construction sector to accomplish CO_2 emission reduction see Gielen (1997). When wood is used for long-life products it could even function as a temporary CO_2 sink.[1] However, few of these studies also pay attention to the innovation characteristics of such options that determine the possibilities for implementation.

The low CO_2 emission characteristics of wood make it a well-suited material to use in CO_2 abatement strategies. However, in many countries forest clearing accelerates as population expands and pressures to exploit natural resources increase (UNEP, 1999). The decline of tropical forests but also the degradation of forests in temperate zones due to current management practices and acidification put the protection of forests high on the political agenda. Therefore, as a compromise between the positive CO_2 characteristics of wood on one hand and deforestation on the other, one can argue for an increase of wood application in long-life products like buildings and a decrease of wood use for short-life products like paper. In order to keep the wood consumption within the regeneration capacity of forests another strategy would be a more efficient use of long-life wood products by means of recycling and product reuse (Fraanje and Lafleur, 1994).

The Netherlands Government follows these strategies in environmental policy formulation. This has resulted in a voluntary agreement between the Dutch construction sector and the government about an increase of wood in the construction sector with 20% in 2000 compared to 1990 (MBB, 1993; Anon, 1996). Even though a 20% increase in the use of wood may be a desirable development, the impact on CO_2 emissions is likely to be small, as the use of wood in the Dutch

[1] In the current IPCC guidelines for National Greenhouse Gas Inventories CO_2 emission, the default assumption for changes from woody biomass stocks is that all carbon in biomass is oxidized in the removal year (IPCC, 1995). However, in the informal IPCC workshop at the Conference of the Parties 5 in Bonn new ways to deal with these temporary sinks were discussed.

construction sector is small. However, the intended policy is significant because implementation would result in the reversal of current trends in materials use in Dutch construction, if implemented successfully.

In this context, this article studies the opportunities to increase the use of wood in the Dutch construction sector. We will also investigate the potential effects on CO_2 emissions related to material use in the Dutch construction sector. In addition we will assess the potential improvement of wood recycling in the Dutch construction sector in a qualitative manner.

Research has indicated that implementation of new technologies commonly faces barriers. These barriers are often not technical but institutional, economic, and social (Sorget, 1998; Velthuijsen, 1995; Gillissen, 1994). Construction is often regarded as a mature, slow to change sector (Gann, 1994). Implementation of new wood technologies in construction is therefore expected to encounter several constraints. By studying the innovation characteristics of the technical options more insight can be obtained in the barriers that might obstruct successful implementation. In this article we therefore also want to create insight in the innovation characteristics of technologies for increased and efficient wood use and discuss how these characteristics might affect implementation.

For two reasons attention to implementation is important to climate and environmental policy makers. First, it gives the opportunity to rank and select improvement options according to their implementation opportunities and likelihood of success. Second, the assessment provides the key to answer the question: which economic and social groups need to be addressed to implement the changes?

The article starts with an introduction to various concepts of innovation in order to relate these concepts in Sections 3 and 4 to wood technologies. In Section 3 we identify options for increased use of wood in the construction sector, determine the CO_2 emission reduction potential of these options, and link characteristics of the options to the innovation concepts. In Section 4 we will present measures to improve the efficiency of wood consumption and link these to the innovation concepts as well. Section 5 discusses the results and how they relate to the existing situation in construction. We end this article with policy implications and conclusions.

2. Concepts of innovation

There appear to be many social and economic factors that influence the implementation of new material technologies (Goverse, 1998). The implementation environment of the wood applications that we study in this article, is predominantly the building sector. This sector consists of many groups with different specializations, such as design, construction or materials supply, that work together in order to create a complex building product. In this sector technical change occurs rather slowly. Empirical studies of innovation and diffusion processes have shown that in many sectors innovations take two to three decades to diffuse to a significant extent (Karshenas and Stoneman, 1995). In the building sector technological change occurs even slower ranging from several decades up to a century (Grübler, 1997).

The implementation of technical changes depends on both the characteristics of the technologies themselves and the characteristics of the socio-economic context in which they take place. Implementation of a technology often means not only the increased acceptance of a new technological artifact, but often implies also socio-economic change. To achieve innovation, changes in the relations between firms dealing with a newly developed technology, such as the supplier–user links, are often necessary (OECD, 1999).

Innovations do not take place in a vacuum but are shaped and framed by the broader implementation environment. Successful innovation depends on factors within this implementation environment, which are often nationally or regionally defined (Tidd et al., 1997; Edquist, 1997). Examples of such factors that influence innovation in the construction sector are strength of the knowledge base, role of the government, nature of strategic alliances, attitude towards costs/quality ratios, and role of the material manufacturers (Jacobs et al., 1992). The influence of these will be taken into account when discussing the implementation and possible policy measures to stimulate the individual technological options studied.

To determine the characteristics of the wood innovations we discern two dimensions: the technical radicality of the innovation and the organizational complexity (required network change) of the innovation.

The first dimension is defined as to which extend skills and expertise of organizations needs to be adjusted to apply the new technology. An example of such a change is the switch of a manufacturer of steel parts to producing plastic parts. It either requires hiring new personnel with prior experience or education, or it requires considerable retraining of the current workforce.

The second dimension concerns the change in the structure of the production network around an innovation. For example, a shift from combustion powered vehicles to electric vehicles requires changes in fuel supply and repair facilities in addition to the new engine components. Different firms than those involved in the existing system will often produce such supporting facilities.

To indicate the level of change on these two dimensions we use several concepts from the literature on innovation in terms of changes involved: incremental, radical, modular, architectural, and system innovations (Henderson and Clark, 1990; Tushman and Anderson, 1986). Incremental and radical innovations represent the dimension of technical complexity of new innovations while modular, architectural and systems innovations represent changes in the dimensions of networks. The two dimensions of change can be combined as innovations usually combine both technical and network dimensions. Table 1 summarizes the classification of innovation characteristics along the technical and network dimension of change.

Incremental innovations are technical changes that can be regarded as a refinement of previous technology (Rogers, 1995). Continuous improvement of the technology on relevant technical aspects is central. Incremental innovations are based upon experience and knowledge in the existing production and use system. In other words, the rules of the technical basis do not change. Typical incremental changes are those where technical improvements lead to greater production capacity. Radical innovations, on the contrary, introduce changes that dramatically divert from the existing technical situation (Wheelwright and Clark, 1992). Previous skills and interactions may become irrelevant. Radical innovations may be recognized by a new set of engineering and scientific principles and may create new businesses and transform existing ones by delivering dramatically better product performance or lower production costs. One well-known historical example is the introduction of the float glass process by Pilkington. The experience and production facilities of the other glass producers became outdated immediately (Freeman and Soete, 1997).

Modular, architectural and systems innovations differ in terms of change in network. This distinction is an important addition to the existing classification in incremental and radical innovations since it explains why even minor innovations sometimes do have a large effect on the ability of established firms to follow the innovation pattern (Henderson and Clark, 1990). A modular innovation does not result in change in networks. It only changes the elements that constitute a product, whereas the linkage pattern between players remains unchanged. Technically, such changes still might be radical. Many phone producers, for example, could not follow the transition from analogue to digital telephones (Henderson and Clark, 1990).

An architectural innovation has a limited network effect. It demands change of the set of associated interacting players; the pattern of linkages between players is changed without necessarily effectuating change within the modules. Architectural innovations limit the usefulness of the organizational knowledge exploited by established firms. A shift in the interaction between knowledge elements still may result in major difficulties in adopting architectural innovations by established firms.

A system innovation implies a large network change. It integrates multiple independent innovations by different groups that must work together to perform new functions or improve the facility performance as a whole; it involves many changes at the same time. The linkages are explicitly among the innovations and entail changes in the links between players. Many groups are involved in a system innovation. In construction an example would be the way in which the development of building modules requires architects, builders and others to work together.

Table 1
Classification of innovations according to the dimensions of technical complexity and network change

Technical complexity	Network change		
	Modular	Architectural	System
Incremental	Small technical change No network change	Small technical change Small network change	Small technical change Large network change
Radical	Large technical change No network change	Large technical change Small network change	Large technical change Large network change

3. Increase of wood use in the construction sector

3.1. Technical opportunities

Before we can apply the innovation concepts to wood in construction we need to create insights in the opportunities for the use of wood in the construction sector. The Dutch construction sector can be split in construction of residential buildings, renovation practices, construction of non-residential buildings and civil engineering. To indicate the possibilities and potentials of increased wood use in the construction sector, in this article we focus on the construction of new houses since this is the only sector on which reliable data regarding material use are readily available.

Contrary to the situation in some other regions, like Scandinavia and North America, wood is not a major construction material in the Netherlands. Concrete and bricks are used in larger quantities than wood products. Especially the application of wood for structural purposes is low. For example, in 1997 the market share of timber frame buildings in new residential buildings was only 5% (VROM, 1997a; van Dijk, 1998).

To estimate the technical opportunities for increased use of wood in the Dutch construction sector we use standardized models of Dutch houses. Three standard houses defined to investigate energy use, material requirements and building costs of new houses (Novem, 1991a,b,c) are a serial house, a single family house and a multi-family house. In our study we will focus on the serial house as reference building (house type A). With a market share of 66% this is the most common type of house in The Netherlands (van Dijk, 1998).[2] In our calculations we will use figures on material use of this reference building by Vringer and Blok (1993). To calculate the potential for increased use of wood we define three other houses consisting of increasing volumes of wood. The three newly defined house types B, C and D are identical to house type A in terms of size and volume. However, the materials used for the various building components are different. As shown in Table 2 wood is increasingly replacing traditional materials for house types B–D.

House type B represents the situation where more building parts are made out of wood than usually is done in The Netherlands. House types C and D represent timber frame houses, which differ strongly from the traditional Dutch houses in production method. Table 3 states the total material use for the four house types. Apart from a shift in materials use, the table shows that substitution of the traditional building materials by wood also leads to large reductions in the weight of houses; house type D is 62% lighter than house type A. Thus, using wood as a construction material could substantially contribute to dematerialization[3] in the Dutch construction sector.

[2] A more detailed model that also takes multi family houses and single family houses into account is not likely to lead to drastically different results since for multi family houses less wood can be used and for single family houses the opposite holds.

[3] Dematerialization here is expressed as a reduction of the total weight of material used.

Table 2
Material use per building component for four house types

Materials (in kg)	Cement				Sand				Gravel				Wood based panels				Wood				Iron				Brick				Sand lime Stone				Gypsum Bricks/panels				Module quantity
House type	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	
Groundwork					4050	4050	4050	4050																													30 m2
Sewerage																																					
Terrace	69	69	69	69	147	147	147	147	297	297	297	297																									6 m2
Fences																	78	78	78	78																	3 m2
Piles[1]	2087	285	285	285	4436	605	605	605	8412	1223	1223	1223					1049	6922	6922	6922	485	70	70	70													8 pile
Foundation[2]	1486	1486	1115	1115	3154	3154	2366	2366	6374	6374	4781	4781									339	339	254	254													75 m2
Exterior cavity wall[3]	213	142	142		855	570	570									676		172	172	423					5112	3408	3408										42 m2
Walls of shed[4]	126				508									261	261	261		239	239	239					3038												25 m2
Insulation																																					26 m2
Inner cavity wall[5]	178	178			716	716									287	287			150	150									10582	10582							35 m2
Non bearing inner walls[6]														745	745	745		197	197	197													3839	756	756	756	57 m2
Bearing inner walls[7]															676	676			423	423									18837	18837					1372	1372	46 m2
First floor	1285	1285	1285	1285	2726	2726	2726	2726	5508	5508	5508	5508									207	207	207	207													46 m2
Floor of shed	336	336	336	336	713	713	713	713	1440	1440	1440	1440									54	54	54	54													8 m2
Second and third floor[8]	4425	4425			8624	8624			18932	18932					975	975			683	683	709	709													990	990	75 m2
Roof construction shed													106	106	106	106	26	26	26	26																	8 m2
Roof construction house	366	366	366	366	777	777	777	777	1567	1567	1567	1567	229	229	229	229	203	203	203	203																	65 m2
Drainpipes																																					73 m2
Gutters																																					65 m2
Front and back doors																	154	154	154	154																	2 door
Shed door																	39	39	39	39																	1 door
Inner doors													38	38	38	38	70	70	70	70	100	100	100	100													8 door
Window frames																	217	217	217	217																	13 m2
Stairs																	237	237	237	237																	1 stair
Plasterwork	73	73	73	73	290	290	290	290																													22 m2
Tiled wall																									208	208	208	208									21 m2
Tiled floor																									100	100	100	100									5 m2
Kitchen													75	75	75	75					34	34	34	34													1 kitc
Skirting board																	15	15	15	15																	68 m
Windowsill													12	12	12	12																					13 m2

[a]In house type A two types of piles are used: 6.75 concrete piles for the serial house and two wooden piles for the shed. For house types B–D all piles are made from wood. The piles have a length of 20 m and contain 1.5 m^3 wood per pile. The top of the wooden piles is made from concrete: length 2 m, diameter 0.31 m. This results in 0.15 m^3 per pile. For 1 m^3 concrete 280 kg cement, 594 kg sand and 1200 kg gravel is needed (Vringer and Blok, 1993). [b]Timber frame buildings are lighter than buildings made from concrete and bricks. We therefore lowered the weight of the foundation that is necessary for the construction of timber frame buildings. We assumed that 25% less concrete is necessary in case of timber frame buildings. [c]In house type A the exterior cavity wall built from bricks. House type B is for 33% covered with wood (14 m^2). We assumed that joists are used of 6 cm by 2 cm. This leads to 0.0212 m^3 joists per m^2 wall. Boards are used as covering with a thickness of 2 cm. [d]The total area of the walls of the shed amount to 22.5 m^2. Again 0.0212 m^3 joists are used per m^2 wall area; 2 cm OSB (high-density wood fiber panel) is used for stabilization covered with boards. [e]The inner cavity walls constitute 22.1 m^3. Joists of 0.38 cm by 12.1 cm are used every 0.5 m. Joists of 10.2 m in length are used on the top and bottom of the walls. OSB (high-density wood fiber panel) (2 cm thick) is used as wood based panel. [f]The non-bearing inner walls are built for house types B–D of a wooden frame covered with OSB (high-density wood fiber panel). Gypsum board is used on both sides as cladding. The total constitutes 57.3 m^2. Gypsum board has a thickness of 1.2 cm and weighs 1100 kg/m^3. The same joists are used as for the inner cavity walls. [g]The bearing inner walls consist of two individual walls separated by a split. For both walls a wooden frame is used that is covered on both sides with OSB (high-density wood fiber panel). On the inside of the two walls OSB (high-density wood fiber panel) is used in turns for noise abatement. On the outside of the two walls gypsum board is used. [h]The wooden construction 2nd and 3rd floor is identical. The total area is 75 m^2. Every 0.5 m a wooden beam (23.5 cm by 3.8 cm by 5.1 m) is used.

Table 3
Total material use for four house types [in tons (1000 kg) per house]

	House A Standard	House B Alternatives	House C Alternatives	House D Alternatives
Cement	10.6	4.2	3.7	3.7
Sand	27.0	13.7	12.2	12.2
Gravel	42.5	16.4	14.8	14.8
Wood based panels	0.5	2.4	3.4	3.4
Wood	2.1	9.2	9.8	10.2
Iron	1.9	0.8	0.7	0.7
Brick	8.5	3.7	3.7	0.3
Sand lime stone	29.4	29.4	0.0	0.0
Gypsum bricks	3.8	1.7	3.1	3.1
Total	126.4	81.7	51.5	48.4

In Table 4 the material related CO_2 emissions are stated for the four house types. To calculate the effect of changing material input in construction on the CO_2 emissions related to material use we used the Gross Energy Requirements (GER) of the building materials as given in Worrell et al. (1994), broken down per fuel type. We used IEA CO_2 emission factors to convert the energy input to CO_2 emissions (IEA, 1997). Table 2 shows that, by changing material use, a reduction in CO_2 emissions is possible of almost 50%. Even though this is a large reduction, it is fairly low compared to the results of Buchanan and Honey (1996) who calculated a possible reduction of 86% (Buchanan and Honey, 1996). The explanation for this may lie in the fact that Dutch houses are constructed with relatively small amounts of steel.

In the period 1995–1999 approximately 427,000 new houses were built in The Netherlands. When these houses would have been built with a maximum input of

Table 4
Total material related CO_2 emissions for four house types (in tons CO_2 per house)

	Standard	Alternatives		
	House A	House B	House C	House D
Cement	8.8	3.5	3.0	3.0
Sand	0.2	0.1	0.1	0.1
Gravel	0.3	0.1	0.1	0.1
Wood based panels	0.3	1.5	2.2	2.2
Wood	0.3	1.3	1.3	1.4
Iron	3.5	1.4	1.3	1.3
Brick	1.4	0.6	0.6	0.1
Sand lime stone	1.3	1.3	0.0	0.0
Gypsum bricks	0.2	0.1	0.1	0.1
Total	16.1	9.9	8.7	8.2

wood, 3.4 Mtons less CO_2 would have been emitted for production of building materials; which is on average approximately 0.68 Mtons per year. This corresponds to 0.4% of the annual Dutch energy related CO_2 emissions in 1995 (CBS, 1997). This CO_2 emission reduction is only a fraction of the total CO_2 emission reduction that is possible when more wood is used in all construction activities in The Netherlands.

3.2. Innovation characteristics of technical opportunities in house type B

In this section we relate the technical options that constitute the house type B to its innovation characteristics. We discuss the innovation characteristics of the increase in the use of wood in the residential construction sector by examining four examples: floors, piles, walls and window frames. Although wooden window frames are also included into the reference house, type A, this options is examined as well, since the use of wood for this product in houses is declining (de Bekker, 1998).

3.2.1. Floors

The wooden floor, which used to be common in Dutch house building at the beginning of the last century, has almost completely disappeared in traditional residential building (Fraanje, 1998). Instead the market share of prefab concrete floors has become high in the Netherlands (80–85%) (Reitsma, 1993).

Increasing the use of wooden floors in the traditional segment would imply a reversal of the current trend. This in itself is hard, because of competition from the now well-established supply structure for concrete floors.[4] Trend reversal is also difficult, because of the high additional costs for wooden flooring compared to concrete floors. Due to the optimization of concrete flooring and the decrease in the development and use of wooden flooring, the additional costs of wooden story floors are considerable (+18% compared to current concrete floors) (Schuurman, 1995). However, improved wooden floors are expected to benefit from a scale effect once its application increases again. Prefabrication will reduce production costs. Also, an increase in the number of suppliers may result in a price reduction.

The return of the wooden story floor requires change by players involved in one part of the building concept: the suppliers of wooden floors. This makes wooden floors a modular innovation. To be a competitive alternative for concrete floors, the product needs to be improved technically to fulfil contemporary requirements, such as standards of (acoustic) insulation. Production of such wooden floors currently takes place only at a small scale. Since the product is not supplied prefabricated, wooden flooring is labor-intensive. Moreover, together with the application of wooden floors, the technical knowledge of wood technology for flooring has gradually disappeared. Therefore, substitution of concrete floors by wooden floors has the characteristics of a radical innovation.

[4] There are only a few companies specialized in wooden floors left in the Netherlands. In contrast to the wooden floor industry, the 35 prefab concrete floor suppliers are well organized; almost 90% of the producing companies are members of the industry association for concrete flooring, a daughter of the Dutch precast concrete industry association.

3.2.2. Piles

Because large parts of the (western) provinces in The Netherlands consist of soft soils, the use of pilework is necessary to obtain a stable foundation. This has been the situation over centuries and cities like Amsterdam are largely built on wooden piles. However, at present mostly concrete piles are used for new building, although wooden piles still have a constant but small market share (SBH, 1999).

The pile driving takes place before the actual building process starts and the type of piles has no consequences for the rest of the building process. So the substitution or improvement of piles only takes place at the level of one compartment. The innovation needed is therefore considered to be modular. Since the wooden piles industry still exists and does not have to make technical changes in the production process to make the piles competitive with concrete piles, we characterize an increase in the use of wooden piles as an incremental innovation.

3.2.3. Walls

Wood is a suitable material for interior non-bearing walls. In Dutch buildings an increased use of wood in walls would either imply the substitution of sand lime, clay bricks, concrete, or gypsum.

In The Netherlands, wooden walls are more often used than wooden floors. However, just like wooden floors, product improvement is required, in order to enhance the use of wood in walls. Technical weaknesses such as insufficient noise isolation, poor appearance of the surfaces and susceptibility for fire should be addressed by the industry (Reitsma, 1993). Since knowledge about wooden walls is still available in the sector, increasing the technical performance of wooden walls is considered to be an incremental innovation. Unless the decision is made to complete the building in in situ cast concrete,[5] the choice of materials does not affect other parts of the building. Therefore, an increase in the use of wooden walls is also considered to be a modular innovation.

3.2.4. Window frames

Window frames are made of wood, metal (aluminum or steel), or plastics. In new residential buildings the wooden window frame is the market leader with over 80% of the market share (de Bekker, 1998; VROM, 1990). At the end of the 1980s this was the case for all building segments,[6] not just for new residential buildings. At that time approximately 90% of the wood used for window frames was tropical hardwood (de Bekker, 1998). In 1995, the market share of wooden window frames for all buildings dropped to 53% (SBH/ITTO, 1995). In renovation, an increasing market in the Netherlands, and non-residential buildings increasingly plastics and aluminum were used.

[5] In situ casting of concrete is a so-called wet building method. The characteristics of wood do not allow for a combination of this wet building method together with a dry wood building method.

[6] Including renovation practices and utility buildings.

Table 5
Estimates of the market share of different materials in window frames (1995) (SBH/ITTO, 1995)

Material	Window frames (%)
Topical wood	24
Non-tropical wood	29
PVC	35
Aluminum	11
Other	1

The suppliers of metal and plastic window frames act as subcontractors in the building process and offer complete products: they not only supply but also install the products. Table 5 shows the distribution of the materials over the total window frame market (SBH/ITTO, 1995).

Approximately 300 suppliers of wooden window frames, 150 suppliers of aluminum, and 150 of plastic window frames operate in the Netherlands (Reitsma, 1993). One producer of plastic profiles dominates the plastic window frame market, whereas wooden and aluminum frame manufacturers buy their materials from various producers.

The position of wood in the window frame industry is well established. Still, innovations are needed to enhance or secure the market share of wooden window frames. The market position of wood is under pressure especially now the use of unsustainable produced tropical hard wood is an issue in the Netherlands and competition with other materials continuous to increase. A shift towards the use of environmentally friendly wood and service oriented supply and installation systems seems to be key elements to ensure a good position of wood in the window frames industry.

The choice of window frame materials is made early in the building process. In contrast to other building parts, it is predominantly the client of the house who decides which materials should be used for window frames (Lourens, 1997). Important criteria for the selection are the life cycle costs. This is not surprising as outer window frames cause the highest repair costs for a new house (VROM, 1997b). Since the supply structure of wooden window frames is mature and the technical improvements are a refinement of previous technology, innovation of window frames is a typical example of a modular and incremental innovation. It requires only minor technical change, limited to actors associated with this building part.

3.3. Innovation characteristics of house type C and D: timber frame building

In this section we determine the innovation characteristics of house types C and D, timber frame buildings. This type of building is a non-traditional building system in the Netherlands; it is currently applied to a limited extent. A transition towards timber frame building implies great changes in the existing brick–concrete dominated building market. A switch to timber frame building can be considered to be the introduction of a new building system for the Dutch building sector.

Knowledge of timber frame buildings is limited to a fairly small group of actors. In contrast to traditional building methods, the building system for timber frames allows for a high degree of prefabrication (Van der Breggen, 1997). Designers and contractors can only switch over to this form of building after being thoroughly informed about timber frame building, because of the total different character of the technique, the building process and the specific sensitivities of the method. The Dutch building sector has practically no experience with designing timber frame houses, methods of process planning, construction calculations, and the required craftsmanship and skills. These factors suggest that a shift towards timber frame building would be a radical innovation.

As far as applied in the Netherlands, timber frame building technique comes from Scandinavia and Canada. In the 1980s this technique diffused to the Netherlands (Dieleman et al., 1997) and still, some of the larger timber frame building companies that operate in the Dutch building market are Nordic or Canadian. As a result both the actual and the cultural distance of these companies to the Dutch building partners is large compared to the local supply of concrete or bricks. Next to these differences, a reorientation for existing building companies towards timber frame houses would require considerable investment in new expertise, logistics, skills and partners. It is not just a change in the product concept that affects the actors in the building process, but it is the introduction of an entire new product concept with different material suppliers, demanding new knowledge and skills and education support. In other words, the substitution of the traditional concrete/brick building by timber frame building is not only a radical innovation but also a system innovation involving many actors and technical changes at the same time.

4. Increased wood recycling

Increasing wood recycling offers the possibility to enhance the resource efficiency of wood. These options, however, are generic and cannot easily be linked to one of the house types given before. The technical potential and the innovation characteristics for the options to increase wood recycling are discussed in this section. However, before discussing the possibilities for increased wood recycling in The Netherlands we first discuss several definitions regarding material recycling.

4.1. Technical potential

We discern three types of recycling: product reuse, material recycling and energy recovery (Worrell et al., 1994). Product reuse is defined as reusing the product in its original form. In case of material recycling, product material is reused as secondary material. In case of energy recovery, the material is incinerated and energy is recovered.

In the case of wood, there are many types of material recycling possible, such as reusing an old beam for production of floor panels or reusing old window frames for chipboard production. The different ways of material recycling vary strongly in the way the structural capacity of wood is retained for future applications. Therefore, it seems useful to differentiate between high quality material recycling and low quality material recycling. In high quality material recycling the structural capacity of the wood is largely maintained while this is not the case for low quality material recycling.

Fraanje (1998) describes a method to use the full potential of resources in their lifetime. This method is called resource cascading and extends the practical lifetime of resources by using it for as many sequential applications as possible by minimizing the quality loss of the resources in each cycle (see Fig. 1).

When Dutch recycling practices are viewed in terms of resource cascading, it shows that some steps in the cascade chain are followed, such as high quality recycling of large beams, recycling wood in chipboard, and energy recycling, but that there is no integrated policy to use the full potential of wood resources (Goverse, 1995). With support of a well implemented recycling strategy based on cascading more high and low quality material recycling could take place in the Netherlands.

To indicate the potential for increased wood recycling it is possible to use the parameter 'total wood life time' (Fraanje, 1998). Current practices in The Netherlands result in an average 'total wood life time' of construction wood of 75–150 years.[7] The high end of this range only occurs for a small percentage of total wood use (Goverse, 1995). It is estimated that the total lifetime of wood in the construction sector can be increased to more than 400 years (IEA, 1997).

4.2. Innovation characteristics of high quality wood recycling

Wood that is released as waste during construction and demolition is mainly incinerated or chipped for recycling. The actual reuse of wooden building parts for new buildings occurs sparsely. As far as it does exist, demolition contractors dominate the second-hand timber market. In addition, some small (ideological) wood reuse firms exist in the Netherlands. Reused wood has some beneficial characteristics: the 'old look', which is attractive to some customers, especially in floors, and the fact that this wood does not start to warp.

Reuse of wood requires no technical change in the application of wood in the Dutch building practice. However, to increase reuse of high quality wood technical change is needed in other parts of the wood chain; careful and selective demolishing of buildings is required as well as further pre-treatment of wood before it could be reused. To increase the reuse potential, adjustments in the design and building phase are required to make the demolition process easier. In addition, the waste separation companies, currently serving the low quality recycling market, need to

[7] This is based on the assumption that a structural application of wood in the construction sector has an average lifetime of 75 years (Fraanje, 1998).

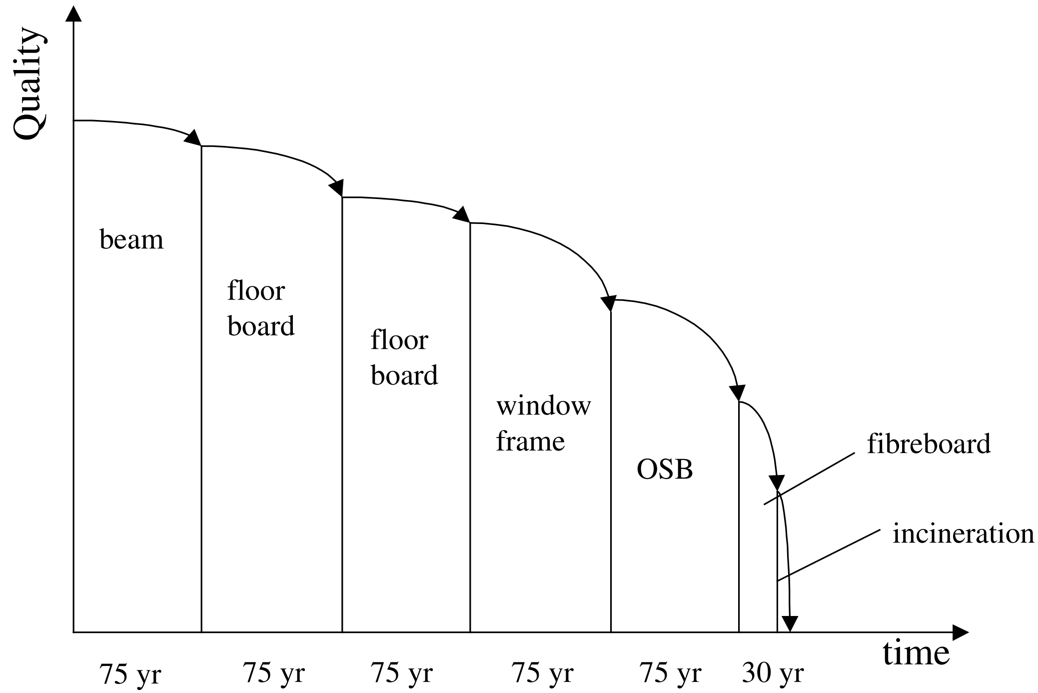

Fig. 1. Potential wood product cascade for pinewood (based on Fraanje, 1998).

become involved in the network as suppliers. They need to include an extra step in their waste separation process to select the large, reusable pieces and provide storage capacity for this fraction. Furthermore, the wood needs to be treated before it can be reused (for example removal of dirt and nails, and standardization of dimensions). This is labor intense and increases the costs of wood for reuse considerably, which deters builders from using it. Unless the old wood is of exceptional quality or origin, builders are not likely to take risks with the application of reused wood when new, certified wood is available.

All parts that need to be involved in implementing increased high quality recycling are already involved in existing building networks. However, new links should be established between the companies involved (waste management industry, demolishers, builders, and architects) to achieve better use of the potential for high quality reuse. Building such a network makes high quality recycling an architectural innovation. Changing technical practices in design, building techniques, demolishing, and waste management provides reasons to classify this innovation as radical.

4.3. Innovation characteristics of low quality wood recycling

Due to increasing disposal costs and a recent ban on landfill for combustible waste, the recycling of wood waste has already been established in The Netherlands. The main players in wood recycling are the builders and demolishers, who deliver construction and demolition waste to waste separation plants where wood waste is separated in two fraction and transported to the chipboard industry or waste incineration plants (thermal recycling). Even though wood recycling takes place, a comparison with other countries learns that the full potential of recycling is not yet utilized. For instance, in some German federal states four types of wood products are separated already on the building site.

The infrastructure for low quality wood recycling exists. However, it needs to be optimized in order to enhance the recycling rates. This asks for a joint effort of different actors related to the building industry: the demolishers, the waste separation companies and the chipboard industry. These actors are not directly linked to the product concept of a building but operate in the building system in the broadest sense. As such, the optimization of recycling is a system innovation. Since it needs optimization of existing practices this option is incremental in character.

5. Discussion

In Fig. 2, the options to increase wood in the construction sector described in Sections 3 and 4 are ordered according to their innovation characteristics along two dimensions. The first dimension is the technical radicality of the option and the second the impact of the option on the existing configuration of players in the socio-economic context.

Most options for increasing the use of wood are modular, whereas the options to improve the resource efficiency by increased recycling requires small up to considerable change of relations between players. Although all measures that are part of house type B are characterized as modular, the technical radicality differs. This shows that modular innovations are not necessarily easy to implement. Although recycling is often used as a single strategy for increasing resource efficiency, Fig. 2 summarizes that high and low quality recycling clearly differ in the demand for technical and network change.

The innovation typology is the first step to understand the changes involved and to derive policy measures that could be helpful to stimulate these wood technologies. The second step is to put these changes in the broader context of the sector in which innovations in construction take place; in our case the context comprises the specific characteristics of the Dutch building sector. In Jacobs et al. (1992) a detailed analysis is made of the Dutch construction sector and how its characteristics influence the implementation of technologies.[8] Important characteristics of the building context identified include:

1. Strong competition on price. In general contracts for construction works are based on total building costs and not on life cycle costs or other quality parameters.

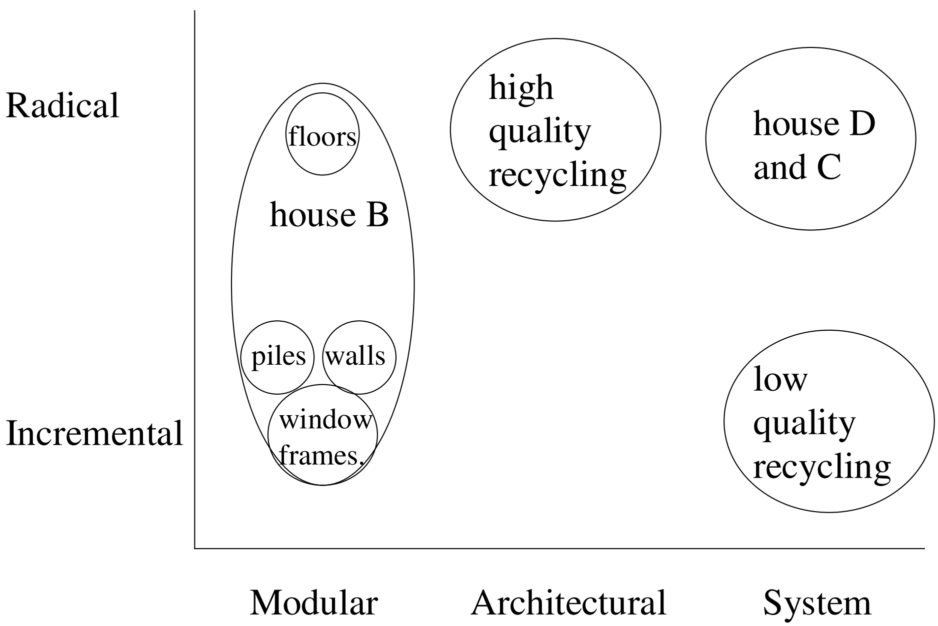

Fig. 2. Innovation characterization of wood technologies based on their implications for change from current (technical) practices and the changes in existing relational structures.

[8] The analysis by Jacobs et al. (1992) is based on the so-called diamond of Porter as introduced in Porter's *The Competitive Advantage of Nations* (Porter, 1990).

2. Cooperation based on temporary contracts between changing configurations of actors, which makes learning processes more difficult and therefore slows innovation in the sector.
3. Strong national orientation, which makes it sometimes difficult for foreign suppliers or builders to penetrate the Dutch building market.
4. Supplier dominated innovations with little innovation in the construction sector itself, with manufactures of non-wood materials being the most important Dutch material suppliers.
5. Research strongly focusing on improving efficiency on the building site, which leads to building time reduction.
6. Strong tendency toward standardization of buildings and building products, which implies that new products should become involved in standard setting at an early stage.
7. Existence of many sector organizations with fragmented coordination, which leads to relative little attention for sector-wide issues such as environmental initiatives and makes intervention by the government difficult.
8. A strong distinction between building stages resulting in poor communication between architect and contractor at the design stage.

To create insight in the barriers related to the wood technologies and the potential measures to overcome these barriers, it is important to know how the identified wood innovations interact with the context. We will describe this in the following.

The characteristics of the modular and incremental innovation in Fig. 2 (piles, walls, and window frames) interact little with the sector characteristics of the construction sector. Basically, the technologies can be fit into the standard production process without too much trouble. However, the fact that material producers that have a large influence on the building process are not focused on the material wood, prevents these technologies from being implemented at a large scale. The general building culture or attitude of the construction sector towards wood hinders these innovations. For window frames, the importance of efficiency and standardization at the building site has already resulted in reduced market shares for wood. Product innovations in this direction seem indispensable for wooden window frames to remain market leader.

At the moment, the characteristics of the building sector constrain successful implementation of the wooden flow. The cost-competitiveness of the sector, its striving towards efficiency at the building site and standardization of building materials and methods, and the fact that the knowledge base is strongly focused on the traditional (stony) materials together makes implementation of wooden floors difficult. Also, project based cooperation prevents the diffusion of knowledge regarding the use of wooden floors.

Timber frame construction has characteristics that relate well to the developments in the building context: timber frame construction is a highly standardized building method and it can be prefabricated which makes the activities at the building site very efficient. However, other elements will hinder successful implementation: the strong national orientation of the sector (much knowledge about this construction method is present at foreign companies), the influence of non-wood material producers, the fact that wood technology is not an important research subject at the universities and other research organizations, and the preference of clients for buildings in stony materials. This will particularly affect acceptation of houses with wooden outer walls such as house type D.

High quality recycling is hindered by a poor interaction between architect and contractor and the fact that life cycle thinking is not part of the building culture. Also the poor interaction between sector organizations is likely to hinder implementation.

Low quality recycling is being implemented fairly well, but further optimization also suffers from the poor interaction between actors and sector organizations.

6. Policy implications

Section 5 showed that few of the options would be adopted in the building context autonomously. In order to stimulate the implementation of wood technologies policy efforts are needed. Based on the specific characteristics of the Dutch building sector, four focus points can be discerned at which policy could be directed.

The first focus point is the way public construction projects are commissioned by the government and other public parties. This is related to the strong competition on price and the organization of the building process in changing configurations of actors (points 1 and 2). When the government in the role of client would like to stimulate an environmental strategy for wood use, minimum requirements could be set for quality of construction in addition to cost-price, and the share of (old) wood use. Moreover, the choice of building organization would influence the characteristics of the building network positively; better integration of design and construction or longer-term partnerships between actors in the building process. Such measures could be further supported by regulations or subsidies to stimulate wood use.

The second focus point is the culture of the Dutch building sector and its customers. This is related to points 4–6. Building with wood is in many respects not part of the building culture and neither does there exist a strong focus on wood recycling. The suppliers of stony materials dominate the market, the research programs and standardization processes. A change could be achieved by increasing information services about wood and wood use in construction, such as initiating demonstration projects and action programs, and addressing the subject in the training programs for professionals. A step in this direction is the wood stimulating program set up in The Netherlands to increase the share of wood with 20%. In addition, much attention is paid to sustainable building practices, including material use, by means of demonstration projects. Wood benefits from its green image as a renewable carbon sink.

The third focus point (point 5) is the attention for research. Research programs with a focus on wood technology could improve the knowledge base in the building sector as well as in the wood industry. Research specifically directed at selective demolition, waste separation, and opportunities for the use of old wood may lead to improved recycling rates.

The final focus point is the stabilization and upgrading of the knowledge related networks (related to all points). Cluster policy aims to facilitate the efficient functioning of knowledge networks.[9] Networks enable the development of innovations built on collective knowledge. Such knowledge networks would encompass strategic alliances of the wood and construction firms with universities, research institutes, knowledge-intensive business services, and bridging institutions. Upgrading of networks includes the involvement of knowledge intensive actors within the network. Since companies within the clusters invest in each other's knowledge base to reach joint advantages, the relations between these companies become more stable. In OECD (1999) ways to build a successful cluster policy are described.

7. Conclusions

In this article we have shown that substitution of wood for other materials in current building practices in The Netherlands can reduce materials related CO_2 emissions significantly. When only some building parts are replaced by wood, technically, a material related CO_2 emission of 38% could be realized per house built. When timber frame houses are considered, a reduction of almost 50% in CO_2 emissions is technically feasible. When the houses that were built in the period 1995–1999, would have been built with maximum input of wood, 0.68 Mtons less CO_2 would have been emitted yearly by the production of building materials. This corresponds to 0.4% of the total Dutch energy related CO_2 emissions in 1995. This CO_2 emission reduction will rise to higher percentages when more wood is used in all construction activities in The Netherlands including renovation and construction of non-residential buildings.

We have classified different options to increase wood use according to their innovation characteristics. Wooden piles, walls, and window frames can be characterized as incremental and modular innovations. Since implementation of these options is not complicated from a technical and network point of few, implementation should be possible in the short term. We calculated that implementation of these options may lead to a reduction of material related CO_2 emissions of 12%.

Wooden floors are more complex to implement from a technical point of view and successful implementation of timber frame buildings requires large policy efforts to overcome severe technical and network related barriers. For a successful implementation of these options, policy is needed that addresses the culture in the Dutch construction sector, the way new building projects are commissioned, the research activities in the construction sector, and the stabilization and upgrading of knowledge and production networks.

[9] These clusters are characterized as networks of production of strongly interdependent firms linked to each other in a value adding production chain.

A large technical potential to increase wood recycling in the Dutch construction sector exists. The lifetime of wood as a construction material could be increased from an average 75 years to a maximum of 400 years, using recycling strategies that are build on an optimized cascading principles. We discerned both high and low quality wood recycling; the innovation characteristics of these two options clearly differ. Low quality recycling already exists to some extent in the Dutch construction sector while there is little experience in high quality recycling of wood. Although they require a different approach, both low and high quality recycling can benefit from cluster policies and policies focused on cultural change.

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